

# The Keck Interferometer Autoaligner

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## ABSTRACT

A key thrust of NASA's Origins program is the development of astronomical interferometers. Pursuing this goal in a cost-effective and expedient manner from the ground has led NASA to develop the Keck Interferometer, which saw first fringes between the twin 10m Keck telescopes in March of 2001. In order to enhance the imaging potential of this facility, and to add astrometric capabilities for the detection of giant planets about nearby stars, four 1.8m 'outrigger' telescopes may be added to the interferometer. Robust performance of the six-aperture instrument will require precise alignment of the large number of optical elements found in the six optical beamtrains spread about the observatory site. The requirement for timely and reliable alignments dictated the development of an automatic alignment system for the Keck Interferometer. The autoaligner consists of swing-arm actuators that insert light-emitting diodes on the optical axis at the location of each optical element, which are viewed by a simple fixed-focus CCD camera at the end of the beamtrain. Sub-pixel centroiding is performed upon the slightly out-of-focus target spots using images provided by a frame grabber, providing steering information to the two-axis actuated optical elements. Resulting mirror-to-mirror alignments are good to within 2 arcseconds, and trimming the alignment of a full beamtrain is designed to take place between observations, within a telescope repointing time. The interactions of the autoaligner with the interferometer delay lines and coude trains are discussed in detail. The overall design of the interferometer's autoaligner system is presented, examining the design philosophy, system sequencing, optical element actuation, and subsystem co-alignment, within the context of satisfying performance requirements and cost constraints.

**Keywords:** Keck Interferometer, Alignment

## 1. INTRODUCTION

The Keck Interferometer is a key element of NASA's Origins program. A number of different modes are available on the instrument.

1. Keck-Keck Interferometry. Pairwise combination of the Kecks can be utilized for:

- (a)  $V^2$  science. Functionally identical to the primary data collection mode of the Palomar Testbed Interferometer (PTI),<sup>1,2</sup> this visibility amplitude mode seeks to exploit the sensitivity afforded by the 10m apertures for initial science operations.
- (b) Differential phase.<sup>3-5</sup> Proposed as early as 1990 by Shao & Colavita as a technique applicable to the detection of massive, warm ( $T > 300\text{K}$ ) planets\*, this mode will directly detect and characterize 51-Peg class 'hot Jupiter' ( $T > 1000\text{K}$ ) extra-solar planets by measuring the phase difference between fringes for the star-planet system at different astronomical bandpasses, such as  $2.2\ \mu\text{m}$  and  $3.5\ \mu\text{m}$ .
- (c) Nulling. Combination of the two Kecks as a nulling interferometer will permit the detection of zodiacal dust shells about nearby stars. Recent lab demonstrations in support of the Keck nuller development have shown promising results.<sup>8</sup>

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\*And received only as a curiosity at that time, since, prior to 1995, it was obvious to everyone that Jupiter-mass companions would not be found that close to their parent star. Subsequent events<sup>6,7</sup> have revised that perspective.

2. Outrigger Interferometry. Four 1.8m ‘outrigger’ telescopes may be added at the observatory site. These telescopes may be used independent of the 10m Keck telescopes for astrometry<sup>9</sup> or imaging.<sup>10</sup> Astrometric observations will combine outriggers in a pairwise fashion to detect Neptune-mass objects about stars out to 30pc at a sensitivity of  $30 \mu\text{as}/\sqrt{\text{hour}}$ ; imaging will be four-way combination for limited 2-3 mas mapping at 1.6-5.0  $\mu\text{m}$  for objects as dim as  $m_K \approx 10$ .
3. Full array imaging. Full six-way combination providing 15 baselines and 10 closure phases on objects down to  $m_K \approx 12$  will enable detailed 2-3 mas mapping of a variety of objects,<sup>10</sup> such as young stellar objects, AGN cores, and evolved star circumstellar environments.

Additional modes, such as single Keck-four outrigger five-way imaging and double Fourier interferometry, are also being considered for the facility.

The first and simplest of these modes requires, at a minimum, no less than a dozen mirrors to be aligned for successful operation of the instrument. For full array imaging, a substantially larger number of optical elements are required to be in precise alignment for proper operation of the instrument.

For these various modes, automatic alignment offers a wide variety of advantages over manual alignment:

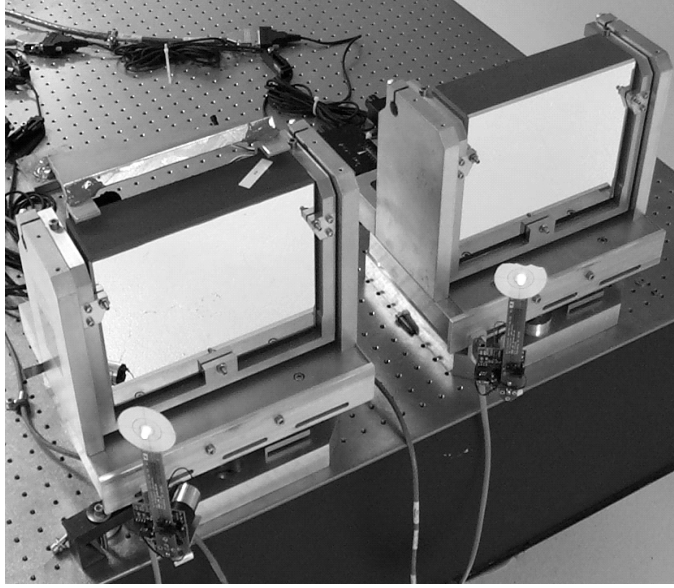
- Autoalignment is potentially much more quickly accomplished than manual alignment.
- Autoalignment is potentially of much greater precision and repeatability than manual alignment.
- Some of the beamtrain mirrors, particularly those located along the coudé train, are inaccessible.
- Disturbances of the laboratory environment are substantially less in performing alignments via remote actuation.

The conceptual design of the Keck Interferometer Autoaligner will be presented in §2, along with its current implementation in §3. Future expansion of that implementation, particularly in the area of support of additional interferometer hardware, is covered in §4.

## 2. CONCEPTUAL DESIGN

This section describes the generalized design philosophy of the interferometer autoaligner. Major tasks of the Autoalignment system, presented in the order that they are to occur:

1. Subsystem co-alignment. At the back end of the interferometer beamtrain, various wavelengths of the starlight beam are split off for use in the interferometer fringe tracker (2.2  $\mu\text{m}$ ), the angle tracker (1.6  $\mu\text{m}$ ), science instruments (1.2 - 14  $\mu\text{m}$ ) and autoaligner (visible). Establishment of a reference system boresight, and co-aligning the various trackers and instruments to that boresight, is the first significant step in bringing the overall optical infrastructure into alignment.
2. Beamtrain beam threading. Once a system boresight has been determined, aligning from mirror to mirror throughout the beamtrain, from interferometer back end to the telescope front end, threads the aligned beam out to the sources of collected starlight. This step covers the greatest distances through the interferometer - from 15 to 50 meters per leg, and up to 200 meters total per beamtrain - and as such, is the most prone to misalignment over time.
3. Telescope-beamtrain co-alignment. Once an optical axis has been established for a given telescope beamtrain, coalignment of the telescope optical axis to the beamtrain’s optical axis will ensure that starlight will thread its way through the basement and to the desired instruments.



**Figure 1.** Mirrors for folding the starlight beams between the Long Delay Lines and Fast Delay Lines for Keck 1 and Keck 2. The flats are approximately 6" high by 9" high. In front of both mirrors are activated Autoaligner targets, swung into each telescope's beam path. Each swing arm consists of a printed circuit board arm, LED, and round paper target surrounding the LED. A second printed circuit board hosts the swing arm motor and support electronics. Each LED (both illuminated in this figure) has been co-located with their beamtrain's central axis at their respective positions.

### 3. CURRENT IMPLEMENTATION

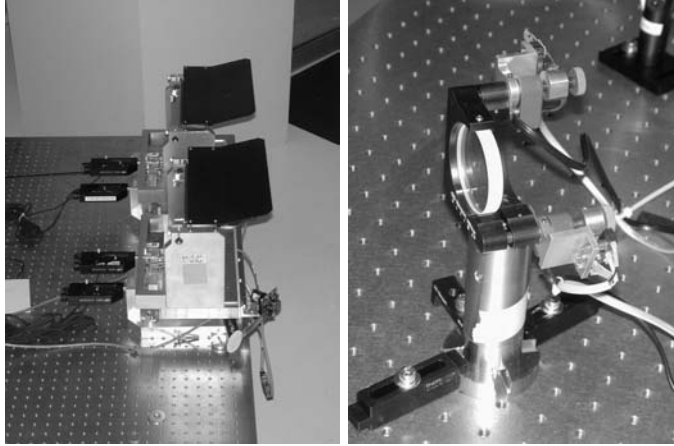
Of the main thrusts of the autoaligner discussed above, the current implementation has concentrated upon development of the overall beamtrain threading. This particular aspect of the autoaligner serves to automate a particularly labor intensive portion of the overall alignment process, and supports beamtrain reconfiguration for sky coverage purposes.

#### 3.1. Hardware

For each mirror mount in a particular beam train, there are three aspects to the optomechanical setup that have been designed and installed to support the autoaligner. First, the altitude-azimuth pointing control of each mount is achieved via computer-controlled actuators. Second, each mount is outfitted with an autoaligner target, which identify the optic axis at that mount's particular location. A pair of mounts may be seen in Figure 1. Finally, at the back end of the beamtrain, an optical detector system views the targets, providing information on actuator steering. The basic implementation is quite similar to the alignment infrastructure found at the Navy Prototype Optical Interferometer,<sup>11,12</sup> which is interesting to note, since both systems were developed independently of each other. Also of particular interest to the Autoaligner are the Long Delay Lines, which contrast to the interferometer's Fast Delay Lines, will require realignment every time they are repositioned (see §4.1).

##### 3.1.1. Actuators

For simplicity of design, we attempted to restrict the number of different types of actuators implemented in the interferometer infrastructure. As a result, there are only two different kinds of actuators utilized in the interferometer beam trains: Newport 850G DC servo long travel actuators, and piezoelectric New Focus Pico-motors (Figure 2). These commercially available, well-supported products were selected as economical choices for long-term operation and support of the autoaligner infrastructure. The 850G and Pico-motor actuators complement each other with regards to their actuation range, precision, and axial load capacity; the 850G



**Figure 2.** Autoaligner actuators: On the left are two 850G-actuated mirrors, each with a pair of the DC servo motors for azimuth and altitude control. On the right is a smaller dichroic optic, with dual Picomotor actuators.

functions to drive our larger optical mounts in the 4" diameter beamtrains (50mm range/ $1\mu\text{m}$  precision/80N force), and the Picomotor is well suited for our smaller mounts at the 1" beam diameter instrument back end (12mm range/30nm precision/22N force)<sup>†</sup>.

All the actuators in the auto-alignment system are under software control utilizing a distributed control system software package called EPICS (Experimental Physics Industrial Control Software). EPICS is running within the VxWorks real-time operating systems. The 850G actuators and Picomotors all use special device support software within EPICS to talk the respective hardware. Two Motorola PowerPC VME single board computers have running EPICS running on them within a single crate.

The 850G actuators are controlled by a Delta Tau PMAC controller installed in a VME crate. The controller actually drives Western Servo amplifiers which drive the Newport 850G motors used to actuate each of the large transport optics (see Figure 2). Also within the VME crate are various Industrial Pack Carrier cards. Two such cards are used to drive a special Picomotor interface module.

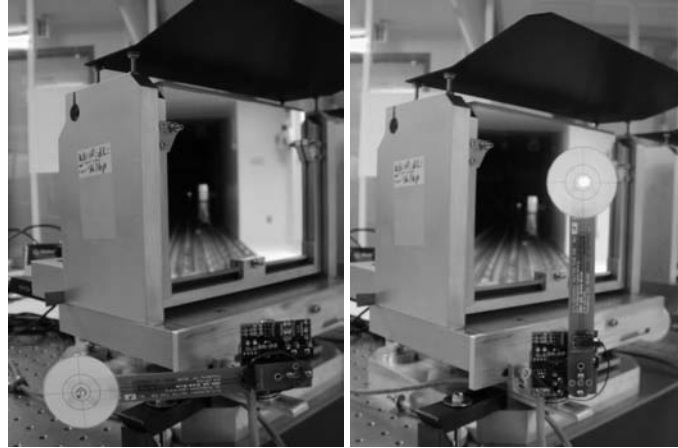
### 3.1.2. Alignment Targets

The Autoaligner targets are a custom-built swingarm mechanism that serves to rotate a light-emitting-diode (LED) from a retracted, unobscuring position to a position coincident with the optical axis of the beamtrain at that particular location (Figure 3). Two printed-circuit boards (PCBs) were designed and fabricated to provide a single Autoaligner target assembly. The first PCB hosts the electrical interface circuitry between the signal cable and the swingarm motor, in addition to the motor itself. The second PCB is in fact the swingarm itself, providing a mounting location for the target LED and an connectorized mount, which electrically joins the swingarm PCB to the motor PCB with a flexible LED power cable; this second PCB is mechanically attached to the swingarm motor via a mounting block that is secured to the motor axis. Limit switches on the motor PCB are tripped by the mounting block as it rotates to the two extents of its rotary motion, and allow for repeatable, two-position on-off use of the swingarm.

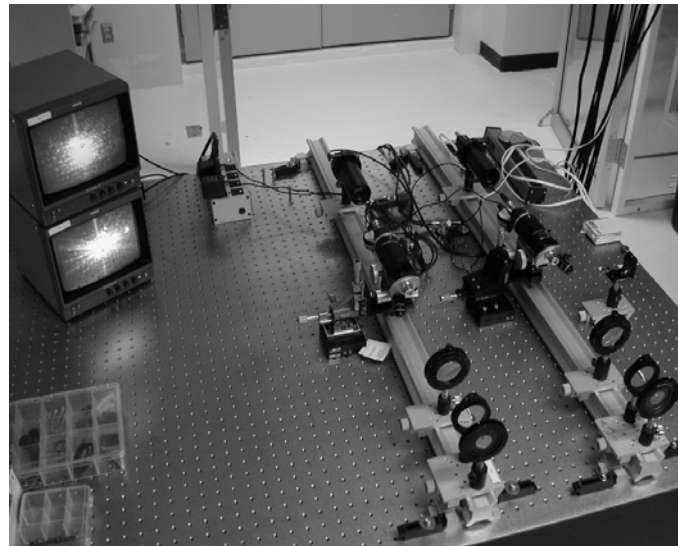
The Autoligner target LED assemblies are also driven via the EPICS software using Industrial Pack Digital I/O modules to turn the target on and off and monitor limit switches for knowledge of current on/off state.

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<sup>†</sup>Specifications taken from technical literature available for each of these products, available online at <http://www.newport.com> and <http://www.newfocus.com>.



**Figure 3.** An Autoaligner target. On the left the target is in its retracted position, clear of the starlight beam. On the right, the target has been swung into position, with its alignment LED illuminated. These bright LEDs are easily seen by the AA camera at the back end of the optical system, even at great distances ( $>200\text{m}$ ).



**Figure 4.** Autoaligner camera.

### 3.2. Autoaligner Camera

The Autoaligner camera is a simple, fixed-focus device consisting of an iris, a singlet lens, and a inexpensive CCD camera, all mounted upon a rail (Figure 4). The setup of this optical system was one of the key design considerations in designing the Autoaligner system. This rather slow ( $f/40$ ) optical system has a large depth of focus and requires no refocussing to observe both nearby and distant LED targets. As a result, the optical axis defined by the singlet-CCD system remains constant, which is required for alignment purposes. The alternative approach considered was use of an alignment telescope, a device that permits refocussing while maintaining an optical axis, but at considerable expense. Given the large number (12-16) of beam trains, each requiring their own Autoaligner system, this approach was deemed to be significantly more economical, while still delivering adequate performance.

### 3.3. Software

#### 3.3.1. Architecture

The Autoalignment software is built utilizing the EPICS software package (see §3.1.1).<sup>13</sup> EPICS is a distributed control system software package that runs on the VxWorks real-time operating system. The decision to utilize EPICS for control of actuators, stimulus targets and sensors was made primarily to preserve compatibility with existing control systems, implemented in EPICS; consisting of control of the two large W.M. Keck Observatory 10 m telescopes. [N.B. The reader harboring a deeper interest in this subject than is presented in this paper's brief overview is encouraged to examine the companion paper Reder, Lockhart & Shupe 2002.] Currently there are four processors running EPICS for alignment functions, the subsystems, also referred to as services, correspond to each VME single board computer (SBC). The services are named: align, to, anc1 and anc2. There are four SBCs within three VME crates in our system. Soon another subsystem called nl will be added for the Nuller.

The top level user interface is called aligner.tcl and uses the W. M. Keck developed Keyword API to communicate to the EPICS implemented alignment functionality. The Keywords are interfaced to EPICS with a Keck developed layer called CAKE (Channel Access Keyword Interface). The aligner.tcl user interface has two modes of operation a manual mode and an automatic mode. In the manual mode the following procedure is executed by hand using various menu items, entry boxes, and sliders on the aligner.tcl user interface.

Automatic alignment mode controls several EPICS sequencers, one instance of a sequencer for each mirror (optic) to be aligned. Each of these sequencers is configured by using a special language called State Notation Language (SNL). SNL is actually processed into a C language code that is run in conjunction with the EPICS sequencer. An EPICS sequence is a programmable state machine.

Currently there are two types of sequencers implemented and under ongoing development. A “beam train alignment sequencer” (btSeq) is used for auto-alignment of large transport optics and another one called “internal instrument alignment sequencer” (iiSeq) is for the automatic co-alignment of back end camera instruments and CCD alignment cameras. Additional Nuller alignment sequencer development is in a pre-prototype development stage.

Our next effort will consist of developing an auto-alignment sequencer that will orchestrate the operation of all EPICS AA sequencers to automatically align the instrument from end to end. This top level AA sequencer no longer uses the EPICS sequencer implementation but will be tightly integrated into the over all Interferometer Sequencer (IS). The IS is currently implemented using a CASE tool called Rhapsody and this will be used to implement the top level AA sequencer.

#### 3.3.2. Implementation

The current implementation of the software is centered around providing the basic actuation functionality upon which the more elaborate alignment sequences can be built. The top-level GUI that drives the Autoaligner functions is shown in Figure 5. A frame from the AA camera is seen in the upper right, centroiding information is given in the upper left, and relevant messages can be seen in the text area at the bottom. Across the middle, three panels allow the user to configure a particular mirror-to-mirror alignment sequence: from left to right, there is a panel for selecting a single mirror sequencer, an actuator status panel, and a sensor selector. At the top of the GUI, there are pull-down menus that allow for robust control of the optical beam path:

- Individual actuators may be initialized, and moved in absolute or relative coordinates.
- Virtual handpaddles are available for mirrors in the beam train, allowing for control of mirror azimuth and altitude actuators, with appropriate rotation matrix and scaling adjustments for moves in terms of alignment CCD pixels.
- LED alignment targets can be activated and deactivated.

- A large number of shutters, with a swing-arm design similar to the LED targets, may be operated to open or close various beam paths through the system. Optical paths to elements such as a boresight alignment laser, metrology lasers, and fringe tracker input fibers can be open or closed for various alignment and calibration purposes.
- Automatic alignment sequences can be activated from this GUI as well.

A typical single mirror alignment sequence consists of the following steps: First, a LED target is swung into place at a given mirror. Then, a frame is grabbed from the alignment CCD camera, and a centroid associated with the LED is computed. Based upon the difference between the LED centroid and the desired boresight, a second mirror, between the activated LED and the CCD camera, is adjusted in altitude and azimuth to co-locate the LED centroid and the boresight. A second frame grab confirms the move, and the LED is deactivated. By threading the beam from mirror to mirror in this fashion throughout the beamtrain, the optical axis can be bridged from the interferometer basement to the telescope. This process was initially done manually, by the user, but is now implemented in `btSeq`, and a similar process is contained within `iiSeq` for instrument alignment (see §3.3.1).

In performing this single mirror alignment sequence, certain special considerations are important:

- For the nearest LED targets, the centroiding algorithm needs to be able to cope with the images of those LED targets being slightly out of focus. Although the optomechanical setup of the alignment camera is optimized to provide maximum depth of focus, this is insufficient to properly focus on the near targets. As such, a traditional center of mass centroiding routine can be improved upon by utilizing a circle fitting approach. Such an approach leverages the knowledge that the LED defocus manifests itself in the image plane as a round spot.
- For mirrors in the coudé train that are mounted upon the telescope, their rotation matrix will need to be adjusted to account for the telescope azimuth.
- Despite the best efforts made during the LED target install, the LEDs that identify the telescope azimuth axis in the coudé train are always imperfectly located. As such, it is necessary to characterize the offset of the LEDs located at the top and bottom of the telescope's azimuth axis from that axis. For the case of the LED at the top of the telescope's azimuth axis, which is mounted on the telescope, the LED spot will appear to inscribe a circle on the Autoaligner CCD camera, the center of which is the true location of the telescope's azimuth axis at that location.

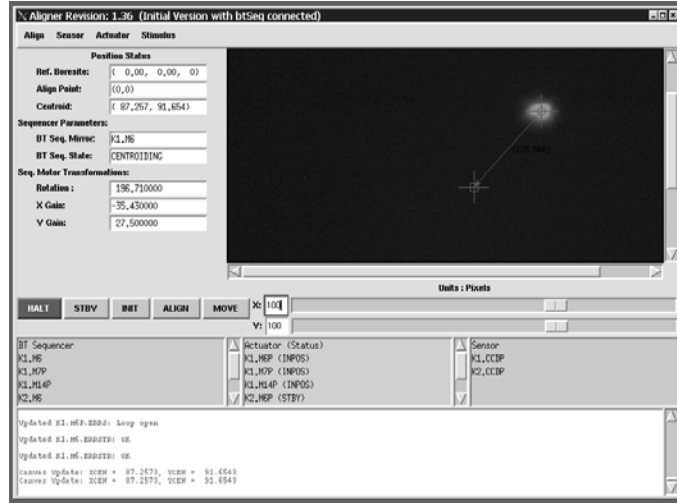
Further high-level functionality is being developed and is discussed in Section 4.2.

## 4. FUTURE DEVELOPMENT

Two areas of development are ongoing for the Keck Interferometer Autoaligner. First, enhancement of the existing infrastructure, particularly in the area of maturing capabilities in support of totally automatic alignment, is an ongoing activity. This is specifically represented by the development of the Long Delay Lines, and the individual instrument co-alignment to the beamtrains. Second, expansion of the overall infrastructure, particularly if the installation of the outriggers takes place at the summit, will multiply the reach and responsibility of the system for maintaining system alignment.

### 4.1. Long Delay Lines

The design of the delay line infrastructure for the Keck Interferometer is split into two parts: large (180m optical path difference, OPD), static amounts of pathlength delay are provided by Long Delay Lines (LDLs), and smaller (30m OPD) dynamic amounts of delay are provided by Fast Delay Lines. Each telescope's LDL sled host two flat mirrors that can be used individually or pairwise for single- or double-pass operation (Figure 6). The design of the LDL sled system is such that a repositioning of the sled requires a repointing of the mirrors on the sled, as well as those mirrors that send light to the sled. The current implementation of the LDL system



**Figure 5.** The current Autoaligner graphical user interface.

is a manual one; repositioning the LDLs requires on-site personnel to unclamp the sled, slide it to the desired position, reclamp it, and then perform a manual beamtrain alignment.

Lab tests currently ongoing are completing the particulars of the rail positioning mechanism, and a successful prototype is already moving up and down its rails at JPL. Once this sled actuation infrastructure has been installed at the summit, automatic moves will need to be coupled with automatic alignments. Towards that end, the LDL sled design exhibits a high degree of commonality with the mirror mount design (Figure 1), using the same Newport 850G actuators to point the optics. An Autoaligner LED target (Figure 3) will be mounted on the LDL sled for each mirror. Aside from a look-up table for initial pointings of the LDL mirrors, the Autoaligner software will treat the LDLs merely as additional, identical mirror mounts in the beam train.

## 4.2. Instrument Coalignment

Prior to threading the beam through the interferometer, from the back end to the telescope, a coalignment must be established between the laser boresight, the instruments, and the autoaligner. Currently this step is performed manually, and for certain instruments, such as the fringe tracker, is necessary on only about a weekly basis, given the stability of interferometer basement environment. Instruments that are aligned to the fringe tracker, such as the interferometer angle tracker, have their alignment adjusted every few observations. Automation of these alignment steps associated with the interferometer backend is undergoing development; the necessary actuation is already in place, and in the case of iiSeq, the initial software is undergoing tests at JPL and at the summit (see §3.3.1). The optomechanical and software environment is being established in such a way as to accommodate expansion to include future instruments such as the nuller and the 6-way imager.

## 5. SUMMARY

The Keck Interferometer is one of the important cornerstones of NASA's Origins program. Effective operation of this complex instrument requires in part a efficient and robust alignment system which, for purposes of operational economy, needs to be automatic. The initial implementation of this system has been successfully demonstrating the chosen approach of active on-axis targets being sampled by a simple optical system at the end of the instrument beamtrain. Development of the operational software and expansion of system to cover all of the instrument subsystems is an ongoing activity, designed to fully automate the alignment process.





**Figure 6.** A Long Delay Line (LDL) sled. Each mirror on a LDL sled is a  $\lambda/20$  flat designed to reflect a 6" clear aperture primary beam, and a 6" clear aperture secondary beam 1" above the primary. The two mirrors on the sled allow for double-pass operation of the LDL. Each LDL has a high degree of both optomechanical and electrical similarity to the large Transport Optics found in the beamtrains (see Figure 1).

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